Middle Man Concept for In-orbit Collision Risks Mitigation, CAESAR and CARA Examples

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This paper describes the conjunction analysis which has to be performed using data provided by JSpOC. This description not only demonstrates that Collision Avoidance is a 2-step process (close approach detection followed by risk evaluation for collision avoidance decision) but also leads to the conclusion that there is a need for a Middle Man role. After describing the Middle Man concept, this paper introduces two examples with their similarities and particularities: the American civil space effort delivered by the NASA CARA team (Conjunction Assessment Risk Analysis) and the French response CAESAR (Conjunction Assessment and Evaluation Service: Alerts and Recommendations). For both, statistics are presented and feedbacks discussed. All together, around 80 satellites are served by CARA and/or CAESAR. Both processes regularly evolve in order either to follow JSpOC upgrades or to improve analysis according to experience acquired during the past years.

Nomenclature

CAESAR	=	conjunction analysis and evaluation service, alerts and recommendations
CARA	=	conjunction assessment risk analysis
COPOC	=	CNES operational probability of collision
CSM	=	conjunction summary message
HIE	=	high interest event
JSpOC	=	Joint Space Operations Center
PoC	=	probability of collision
O/O	=	owner/operator
OD	=	orbit determination
OSA	=	orbital safety analyst for CARA missions at JSpOC
MM	=	Middle Man
NDPP	=	non-traditional data pre processing
SP catalog	=	JSpOC precise (Special Perturbations) catalog which is not public
USSTRATCOM	=	United States Strategic Command

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I. Introduction

Because of the ever-increasing amount of orbital debris, the possibility of a satellite collision with space debris or another satellite is becoming increasingly likely. This phenomenon concerns all orbit altitude regimes, particularly Low Earth Orbit (LEO) but also Geosynchronous Earth Orbit (GEO). Therefore Space Agencies, such as NASA or CNES, adopted operational collision risk monitoring. After the first collision of an operational satellite in February 2009, a major change occurred in USA: JSpOC started to predict close approaches for all the operational satellites and to send information messages describing close approach risks to operators worldwide. In July 2010, Conjunction Summary Messages (CSM) which are complete information to assess a collision alert, were made available for all by USSTRATCOM with a secured access on the Space Track website.

II. Conjunction Assessment with CSMs

Conjunction Summary Messages (CSM) are real satellite protection data provided by JSpOC for all active satellites. They are made available on Emergency Criteria which are Time of Closest Approach (TCA) within 72 hours combined with a miss distance criteria. For LEO the overall miss distance must be lower than 1km with radial miss distance lower than 200m, and for higher orbits (GEO and MEO) overall miss distance must be lower than 10km. CSMs include: identification of the 2 objects, TCA, and for each object: position, velocity, dispersion and some orbit determination characteristics.
Nevertheless, CSMs are advisory and informational messages only and are not directly actionable: they don't provide a direct recommendation to perform an avoidance action and of course they cannot take into account the operational constraints of the asset.

Therefore, satellite Owner/Operators (O/O) must:
- Evaluate the level of risk of the conjunction according to their own criteria;
- Decide whether to perform an avoidance action, in other words detect among all conjunctions described with CSMs the High Interest Events (HIE);
- Compute the avoidance action taking into account the operational constraints.

Conjunction Assessment using CSMs is not so easy to perform, especially when a conjunction description is given through multiple CSMs. While each CSM provides sufficient information to compute a unique evaluation of the level of risk and can provide enough information to determine if O/O criteria for avoidance actions are met, multiple CSMs do not always refine the description with consistent data. Each new CSM comes from a new Orbit Determination (OD) at JSpOC. Since OD is very sensitive to measurements (sensors distribution, dispersions, biases …) and since realistic covariance is not easy to evaluate, successive OD are not always consistent. In such cases, it is not easy to evaluate if O/O criteria for avoidance action are met and which avoidance action should be chosen.

Conjunction Assessment using CSMs implies:
- Consistency checks must be done using all CSMs;
- O/O must be ready 24/7 to perform the analysis with very short notice;
- Difference (if any) between CSMs must be explained : each CSM must be double checked and JSpOC OD for primary object must be compared with the O/O OD;
- Variation of dispersion should be analyzed: "realistic" dispersion inflation or reduction, on primary and on secondary object, can lead to very significant increase of the Probability of Collision (PoC). "Realistic" depends on the OD characteristics and relies on experience feedback. A low PoC conjunction can hide a very risky one.

After conjunction assessment risk analysis, only very few CSMs lead to an avoidance action, but those HIE conjunctions must not be missed.

Conjunction Assessment is a two-step process followed by a third step for collision avoidance action:
- <u>Step 1 : close approach detection</u>

It requires the maintenance of a catalog of space objects. The catalog is the main source to perform screening and detect close approaches for active satellites. It produces conjunction messages to notify O/O of potential risky conjunctions.

Today, JSpOC is the single 24/7 global provider.

- Step 2 : risk evaluation for collision avoidance decision

It consists of the analysis of all available CSMs describing a conjunction with the capacity to do so 24/7. It produces an evaluation of the level of risk of the conjunction in order to detect HIE, alert and recommend avoidance action. There is a need for few entities delivering to O/O Step 2 service; this is the Middle Man (MM) concept.

- Step 3 : collision avoidance action

Once both steps of Conjunction Assessment are complete, the O/O must evaluate the risk assessment, make the collision avoidance maneuver decision and realize the maneuver.

III. Middle Man Concept

The Middle Man (MM) is in charge of risk evaluation for collision avoidance decision (Step 2). The interface between provider of information messages describing detected close approaches and O/O evolves as described in Fig. 1.

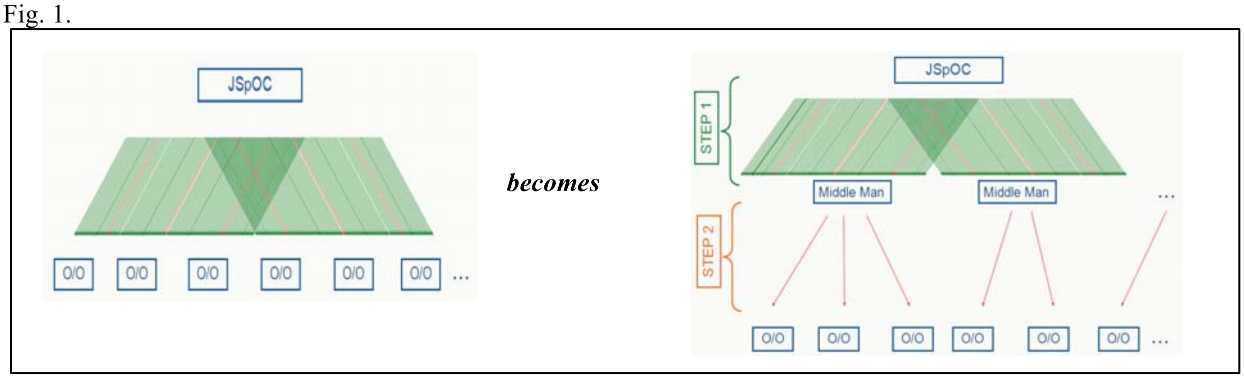

Figure 1: Interface evolution with Middle Man (MM).

In an organization that uses a Middle Man, the satellite O/O is only activated by MM for HIE, in other words when an avoidance action should be considered according to its own criteria (predefined with MM). MM is in charge of:

- Sending on daily basis O/O ephemeris to JSpOC;
- Analyzing all available CSMs;
- Finding the HIE conjunctions for which an avoidance action is needed according to O/O criteria;
- Sending collision alert to O/O in case of HIE;
- Providing elements to O/O in order to enable decision on an avoidance action;
- Supporting O/O to choose the avoidance action (to understand the level of the conjunction risk and to size the maneuver).

To enable fruitful dialogue between O/O and MM, a collaborative work environment between O/O and MM has to be established.

The collaborative work environment between O/O and MM has the following functions:

- Allow real time connections (phone, e-mail). The alert to O/O should be closed loop (acknowledgement of reception) and an interactive dialogue is necessary to ensure MM support;
- Ensure to share the same vision of the situation through the use of the same tool and secure exchange data means;
- Enable different levels of information visualization.

IV. First Example of Middle Man: CARA Process

The NASA Robotic Conjunction Assessment Risk Analysis (CARA) team performs routine collision risk assessment for all NASA unmanned missions.

Each day, predicted ephemerides for each mission are provided to the JSpOC, where they are screened against the Special Perturbations (SP) catalog. JSpOC personnel generate close approach predictions using screening volumes

defined by NASA and updated annually [Ref Narvet], an example of which is given in Table 1. The volumes have several levels used for different purposes. The Monitor Volume is the largest safety volume and serves as the initial reporting filter. All objects that are predicted to violate the Monitor Volume are reported to the NASA Robotic CARA Team. This product is provided each time the catalog screening is performed and it includes the catalog identification number of the secondary object and the Radia/In-Track/Cross-track (RIC) miss distance components and velocity components at the time of closest approach. The Tasking Volume is a smaller volume, and close-approach predictions that fall within this volume require further analysis. The OSA will manually examine the orbit determination solution for both objects and request additional tracking on the secondary object if necessary so that a more accurate orbit can be determined. For each Tasking Volume violation, state vector and state vector uncertainty information is provided to the NASA Robotic CARA Team. This information allows for the collision probability to be calculated. Additional orbit determination details such as the fit-span, tracking information, and force modeling parameters for both the primary and secondary object at the time of closest approach are also included. The Reporting Volume is a smaller volume than the previous two. Predictions that fall within this volume are considered a higher threat than those that simply fall within the Tasking Volume. As such, once a close-approach prediction falls within the Reporting Volume, the event is reported to mission operators. Numerical values of screening volume sizes are set for several altitude bands through the analysis performed on a yearly basis to account for updates in solar activity, tracking network capability changes, and/or the debris environment.

Close approach data is sent by JSpOC to the CARA team at NASA Goddard Space Flight Center for processing, storage, and analysis. The process includes:

- Re-formatting of O/O ephemerides to JSpOC format and transmission of files to JSpOC;
- Analysis of all close approach predictions sent by JSpOC;
- Identification of HIEs based on analysis of JSpOC data
- Recommendation to O/O on whether to perform an avoidance maneuver and, if so, the timing and size that will mitigate the event

Screenings are performed 7 days out for LEO missions and 10 days out for GEO/MEO/HEO missions. Figure 2 shows an overview of the process. It also includes a third step, in which the O/O performs risk mitigation as needed. The O/O retains responsibility for accepting risk for his asset, so the O/O makes the final decision on whether to maneuver the spacecraft to mitigate the risk posed by a close approach.

Table 1: Safety Volume Definitions Example

	Orbit Regime	Radial (km)	In-Track (km)	Cross-Track (km)
Monitor Volume (ellipsoid)	All	±2	±25	±25
Tasking Volume (box)	Perigee between 1200 km and 2000 km	±0.5	±14	±12
Tasking Volume (box)	Perigee between 500 km and 750 km	±0.5	±17	±20
Reporting Volume (box)	All	±0.5	±5	±5
Watch Volume (sphere)	All	1 km stand-off radius		

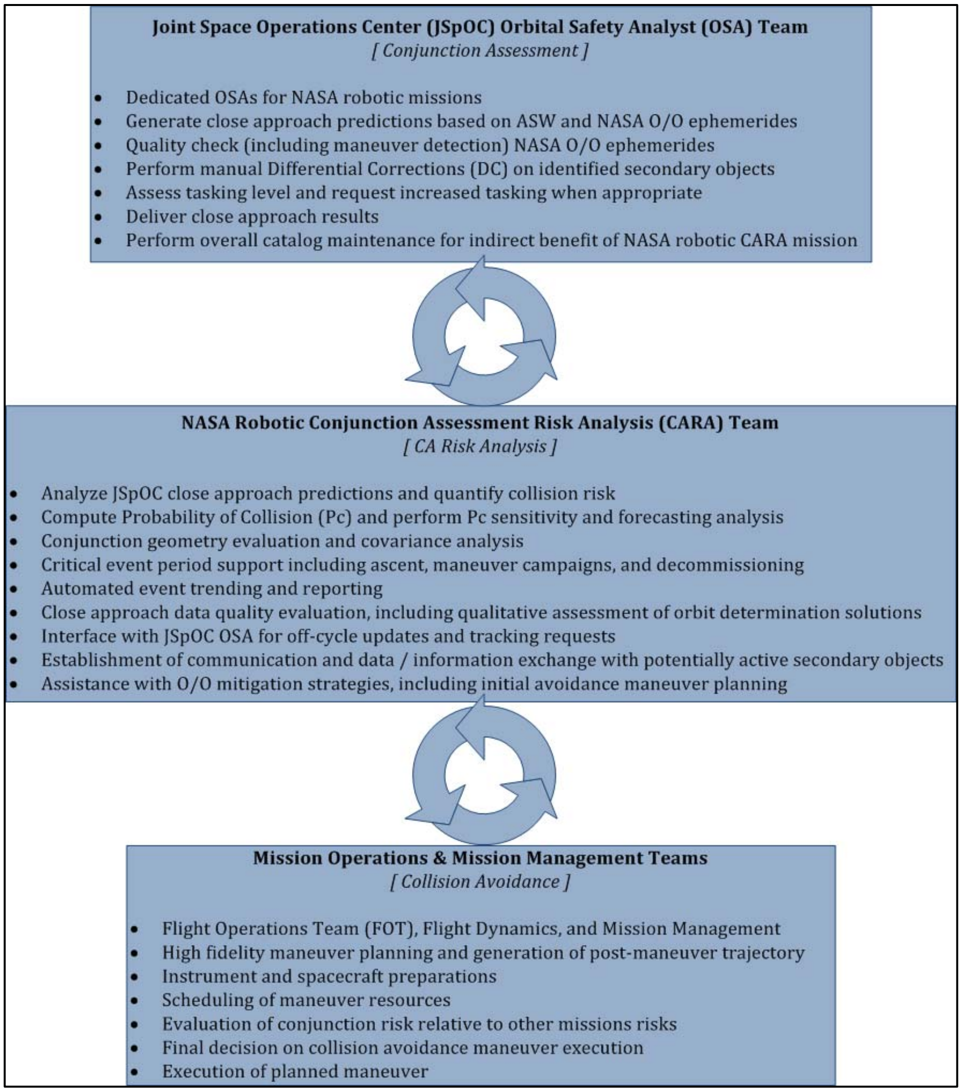

Figure 2: NASA CARA process

Before launch or the start of CARA service, the interface and operations plan between CARA and the O/O is defined in a signed agreement. The agreement provides information on satellite capabilities and maneuver constraints as well as product delivery times and formats.

V. Second Example of Middle Man: CAESAR Process

CAESAR stands for “Conjunction Analysis and Evaluation Service: Alert and Recommendations”. CAESAR is the French MM and a probative public service delivered by CNES using combined operational capacities of French defense and CNES.

For all Earth orbit regimes, CAESAR includes:

- Daily analysis of O/O ephemeris (with station-keeping maneuvers), data format transformation and sending to JSpOC;
- In-house screening for O/O ephemeris against all the secondary space object orbits provided in the different CSMs delivered by JSpOC;
- For LEO orbits, in-house screening for O/O ephemeris against Almanac (precise catalog of space objects in the field of view of the French surveillance radar GRAVES, Almanac is maintained at CNES by CAESAR team);

- Analysis of all CSMs (24/7). From JSpOC, CAESAR team gets CSMs using annually updated NASA screening volumes [Ref Narvet], as soon as JSpOC takes them into account;
- Identification of HIE according to agreed criteria on PoC, uploading CNES CSM and JSpOC CSMs on CNES dedicated secure website SpOD, e-mail sending to alert O/O with phone confirmation;
- Support O/O in decision making and sizing of the collision avoidance action thanks to JAC dedicated software.

For LEO orbits, CAESAR includes additional actions: when feasible, OD of the secondary object using available tracking means is performed for instance when uncertainties provided in JSpOC CSMs need to be confirmed or improved.

Figure 3 shows the information flow of CAESAR from a high perspective.

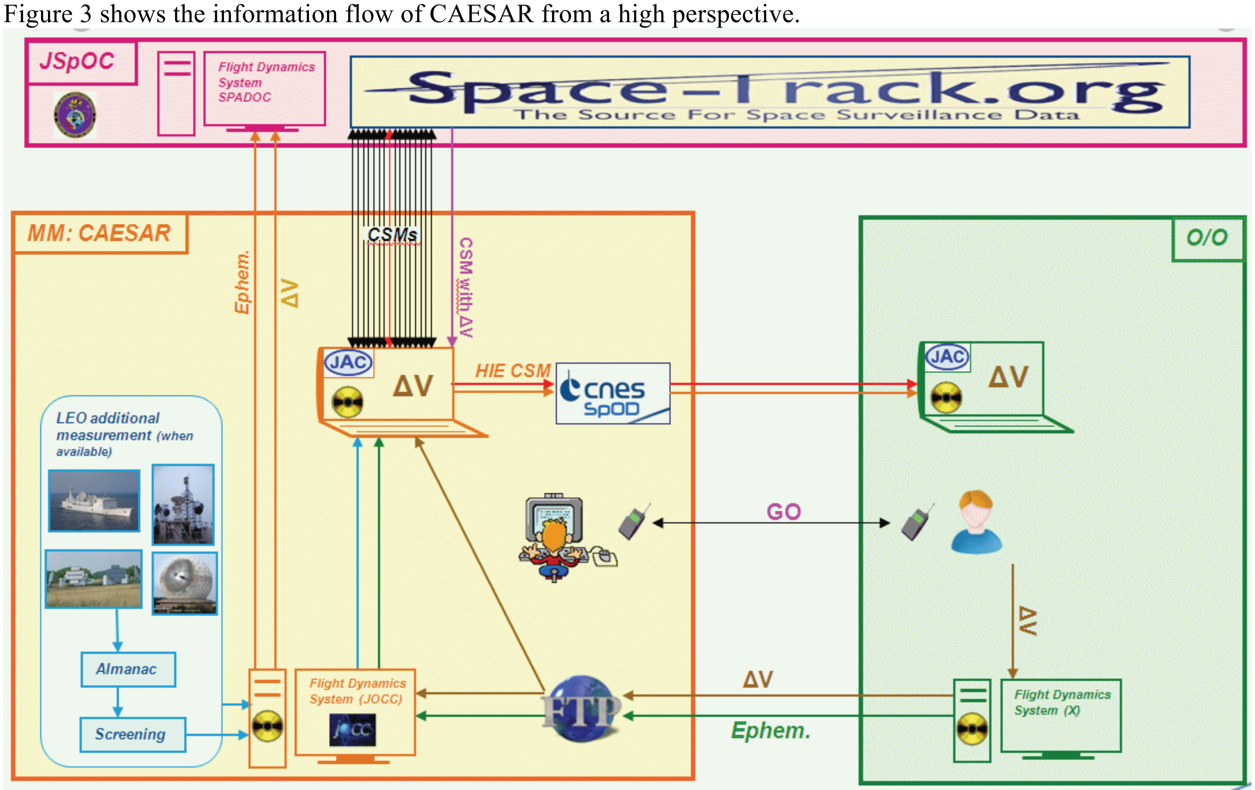

Figure 3: Middle Man CAESAR

The Orbit Computation Center (OCC) from CNES Toulouse Space Center is the operational entity providing CAESAR. Before starting service delivery, the operational interface is defined between CNES/OCC and O/O. The operational interface defines satellites constraints, PoC threshold to alert O/O, O/O ephemeris format, and maneuvers plan format. CAESAR is mainly based on CNES capabilities. The use of other means (French Defense means, German TiRA radar) is not guaranteed. In any case, O/O remains responsible for the decision to perform or not an avoidance action.

Subscribers to CAESAR can rely on the recognized CNES expertise to analyze CSMs (on average 15 satellites per year get the service since beginning of JSpOC information messages delivery) and this expertise is sustained by the scaling factor. Subscribers do not have to develop the required specific skills which includes expertise and software, do not have to maintain an operational team with the capacity to handle CSMs 24/7, and do not have to adapt to specificities and evolutions of CSMs providers. To illustrate potential evolutions, CSM will be replaced by Conjunction Data Message (CDM). CDM is a standard message validated in June 2013 at CCSDS level [Ref CCSDS] and CDM will allow choices to CDM providers since there are many optional fields which may be populated to add additionaln information over what the CSM allows. Subscribing to CAESAR lets to O/O the strategic choice of his residual risk level (O/O chooses the PoC threshold to get alerts from CAESAR).

Subscribers to CAESAR sign a contract with CNES and financially contribute to operations and maintenance.

VI. Similarities and Particularities

CARA and CAESAR are both MM: they work closely together to improve the quality of the analysis they provide to their O/O subscribers. They combine their experience and capacities: CARA has a privileged access to JSpOC data which for instance enables statistics to define common criteria (the two teams work on "non-actionable criteria" this way) and CAESAR has chosen Agile Modeling which enables efficient and innovative development of tools (the two teams share the use of one of the CAESAR tool, JAC [Ref Laporte]).

Meanwhile, CARA and CAESAR process have differences.

Both groups perform probability-based risk assessments, however, there are subtle yet distinct differences in how this collision probability is computed and used operationally. The CAESAR team computes and uses the CNES Operational Probability of Collision (or COPoC) for evaluating the level of collision risk. The COPoC is similar to the so called "max PoC" [Ref Alfano], where the combined covariance matrix of the primary and secondary is scaled and the PoC is recomputed until the combination of scaled covariances that achieves the highest value of PoC is determined. The COPoC, in contrast to the typical max PoC computation methods, only uses realistic variations of the error (covariance) based on the OD data available in the CSM and scales independently the covariances of the primary and the secondary. For CAESAR, an HIE is triggered whenever the COPoC is higher than the agreed threshold. For CARA, HIEs are identified by a combination of PoC and OD quality assessment analysis. As risk mitigation strategy, CARA recommends targeting maneuvers that provide a post-maneuver PoC less than 1E-10. As risk mitigation strategy, CAESAR recommends targeting maneuvers that provide a post-maneuver COPoC less than 1E-05. CAESAR does not target 1E-10 in order to take into account the residual risk level due to non-catalogued objects but considers sensitivity analysis to errors (COPoC instead of PoC).

Also, there are differences in how the groups communicate with customers. CAESAR does internal analysis of the events and only communicates with the O/O when a HIE is detected and warrants discussion. CARA provides daily summary trending data to O/O and then additionally contacts the O/O for HIEs that warrant action. Finally, all of CARA's screenings are performed at the JSpOC, but CAESAR can do their own screenings with the Almanac data, to produce their own CSMs. CARA does not currently produce CSMs.

VII. Benefits of Using the Middle Man Construct

There are many benefits of using the MM model for conjunction assessment (CA) services. First, using a MM offers the possibility of having a center of expertise for CA support. The MM team has a great deal of experience analyzing close approach events. Understanding the nuances of the uncertainties in the PoC and other related calculations is important in understanding the risk, and the more experience an analyst has in performing these calculations the better their risk assessment. If each O/O were to do the risk analysis themselves, they would not see as many close approaches and not accumulate the requisite experience as quickly. Second, the MM can work closely with the screening provider, understanding their process, procedures, and software. This enables the MM to ask the necessary questions, coordinate getting additional data as needed, and make the most efficient use of the combined resources to get the best data for the least effort. If each O/O had to learn about the screening data provider's process, they would bog down the data provider by all asking the same questions to try to gain an understanding of the process, and they would each use resources to develop their own understanding of that process and sign an agreement with the provide describing the interface. Third, the MM can develop and maintain the software necessary to analyze the close approach data, preventing every O/O from having to do the same. The MM can also provide standard ephemeris formats for exchange (converting file formats as necessary). Fourth, the MM can invest a portion of its funding to perform research and development, to develop new algorithms and software of benefit to all O/O customers. If each O/O were to spend resources, they would not have such a large funding pool and would probably not be able to perform major improvement research. Many efforts may be duplicative across O/O, not allowing effective use of resource pools. Finally, the MM can coordinate the sharing of lessons learned across O/O teams, allowing customers to benefit from the experience of others. CARA and CAESAR estimate that using the MM concept saves their O/O customers about 0.5 staff-years per operator per year, assuming that they are

provided with fully functional software to perform their analysis and assuming that they don't plan to do any additional analysis beyond that required to support real time operations.

VIII. Conclusion

Space Environment protection concerns everyone and is the interest of all. In this scheme, the JSpOC delivers CSMs which are the best available data to mitigate in-orbit collisions.

Each actor of the two steps of CA process is working for improvements with Space Environment protection as main goal.

- For Step1 (detection of close approaches), JSpOC is working to widen its operational capacity in order to more routinely perform screenings using O/O ephemeris with its Non-traditional Data Pre-Processor (NDPP) system development and implementation later this year.
- For Step2 (risk evaluation for collision avoidance decision), CARA and CAESAR are working to improve their risk assessment by developing new methods and software.

There area many advantages of a MM model for conjunction assessment. The existence of a MM allows standardization of a complicated process such that missions have access to experts who have a great deal of experience analyzing close approaches. The MM provides a single point of entry/exchange between the screening data provider and the O/O, streamlining data exchange. The MM understands the screening process details and can ensure that the O/O receives the best service possible. The MM can also provide standard ephemeris formats for exchange (converting file formats as necessary).

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